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Transmission Characteristics of Evanescent Lamb Waves through a Tunneling Region: a Chance for Backward Propagation

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Abstract

Evanescent waves are characterized by the exponential decay of the amplitude along the propagation direction, such that no phase velocity could be properly defined and the concept of propagation itself has to be properly redefined. However, evanescent waves can carry energy beyond a tunneling region where they are produced, and their effect in the forbidden region may be properly inferred by the outgoing wave. In the present paper, evidence of evanescent Lamb waves on a plate is given, as they are produced within a forbidden region where thickness is properly reduced and the acoustic modes are above threshold of propagation. However, the coupling of modes at each line boundary between different regions makes it difficult to single out the tunneling mode alone, since all modes share the same frequency. Therefore, we resort to the propagation of the backward S1 mode, that can be properly isolated from all the others. That makes the problem of refraction/reflection of backward propagating modes at a boundary, a problem by itself to be investigated and makes it worth to perform experiments on it. This is done in the present paper, as well, by detecting the acoustic field of a backward propagating Lamb mode reflected from the end boundary of a steel plate and the focusing effect from such a boundary is put in evidence in the case that a forward propagating mode is reflected as a backward propagating one.

Keywords: Tunneling; Lamb Waves; Backward propagation

1. Evanescent modes and superluminal propagation

It has been long a time that superluminal propagation of waves, i.e. waves travelling faster than light, has been pursued in the attempt of testing the definition itself of signal, and the limits set to its transmission by the principle of causality. No limitation, really, exists to the phase velocity of a propagating wave, which can be higher than that of light [1], but when a packet is formed to produce a signal, group velocity has to be taken into account, and in

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order for a signal not to be distorted, all the spectrum components should be theoretically transferred at that velocity, which is not possible due to the causal relationships of the dispersion curve [2, 3].

Evanescent waves have been experimented, as well, in optics and microwave technology as a candidate to transmit fast signals across two points: indeed, no energy is carried on along the path of an evanescent wave and propagation is not a correct word for such a wave. Energy is really tunneling through a forbidden region, where waves get evanescent, and they cross the region instantaneously, such that the question raises as to which part of the wave should be considered to be targeted for being considered the starting and/or the arriving point of it. For the case of a particle crossing a classically forbidden potential barrier, it has been firstly theoretically predicted [4] and later experimentally ascertained [5] that the crossing time first grows up linearly with the barrier width and then stands at a constant value independent from the barrier width (the so-called Hartman effect [6]), thus demonstrating a time close to zero for the crossing of any additional length. Transit time measurements in quantum mechanics, however, have to intrinsically deal with the perturbation problems related to the invasive detection of particles. On the other side, in electromagnetism and acoustics such problems are overcome by the huge number of identical particles (photons/phonons) that one may experiment on and perturbation is reduced to a minor effect.

Some of the authors replicated the experiment [7] by letting evanescent acoustic waves cross a region of definite width: Lamb waves have been generated and propagate in a thin plate of aluminum, where they impinge normally onto a boundary of a thinner region, where they become evanescent, and then recover their propagating nature on emerging out from the forbidden region into a region of the plate, which shares the same characteristics of the first one. Generation and detection of acoustic plate modes have been done through the use of the wedge technique, that allows one to tune at any given frequency on a particular mode, depending on the angle of incidence, thus on the wave vector component parallel to the plate limiting surfaces. However, due to the limited area of the emitting and receiving transducers, several modes can be contemporarily generated and detected. This is a strong penalization in our case, when the detected signal is small enough and one has to detect that mode alone which crossed the forbidden region as an evanescent mode. Indeed, both at the entry and at the exit boundaries between the forbidden and the allowed regions of the plate, the considered generated mode couples to all the others - though with different efficiency - and some of the newly generated modes may happen to be detected together with the mode to be investigated, thus adding undistinguishable spurious signals to the correct one. In order to overcome this difficulty, we resorted to experiment with a backward propagating mode, that is a mode whose wavefront moves into the opposite direction with respect to where its energy travels [8]. This is the first symmetrical S_1 Lamb wave near its zero value wave number β, as represented in Fig.1, for the case of an aluminum plate; where ω, is the angular frequency, b, the plate thickness, V_S, the velocity of the shear waves in the medium.

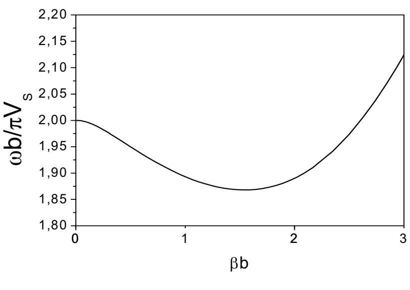


Fig.1 Dispersion curve of mode S_1, where the negative slope region allows backward propagation.

Table 1. Transit time at different barrier lengths and corresponding tunneling velocity

L (mm)	τ_{ph} (μs)	V (m/s)
3	1,06	2830
8	1,34	5970
13	1,35	9630
18	1,35	13333
23	1,35	17037
28	1,35	20740

A backward travelling wave pulse was generated, 20μs long, on a b=2.05mm thick aluminum plate and sent to impinge onto the forbidden region through the wedge coupling technique, with all the others potentially generated modes moving into the opposite direction; at the line boundaries between different thickness regions, as well, all spurious modes will move away from propagation direction of the backward mode and only this mode will be detected beyond the forbidden region. This region is b'=0.7mm thick, well below the cut-off point of the mode, that then 'crosses' the region as an evanescent mode, its amplitude smoothing down up to the end of the thinner region where it flips back to the propagating mode and propagates as such in the final region with a much lower amplitude. Several 'transit times' have been tentatively introduced in connection with a forbidden barrier, and corresponding definitions been given: we followed the one that takes the position of the half value of the pulse amplitude as a detectable element of the wave, that corresponds to the so-called 'phase time' τ_{ph} [9]. Different values of the forbidden region length L have been experimented on, all for the same value of the central frequency of the backward wave, f=2.1MHz, and for the same values of the thicknesses of the propagating (b=2.05mm) and of the forbidden (b'=0.7mm) regions; results of the corresponding evaluated phase times are reported in Table 1, together with the hypothetical tunneling velocity V of the wave pulse within the forbidden region.

Notably, a regime value of the transit time (τ_{ph} =1,35 µs) is found for sufficiently extended regions (L>8mm) of the tunneling barrier, that is the Hartman effect prediction, to which there corresponds an ever increasing transit velocity V. This may correspond to a 'superluminal' electromagnetic velocity, if one considers the value $V=V_S$ as the limiting velocity in the case of the acoustic Lamb propagation.

2. Propagation of backward mode

The use of backward propagating modes, however, stimulated several considerations, as to where the energy flows after impinging onto a boundary between two different media, in our case a line boundary between two plate regions. Experiments were, therefore, carried on relative to simple reflection/refraction phenomena and the image forming of a boundary set in evidence through mode coupling between forward and backward propagating modes.

First of all, a check was directly done on the phase of the backward mode S_1, as it decreases on increasing the distance from the emitting transducer. Figure 2 reports such dependence for the geometrical case of the plate described above, for three different values of the frequency f=1,45 MHz (triangles), 1,48 MHz (squares), 1,51 MHz (circles), that correspond to values of the parameter $\omega b/\pi V_S$ reported in Fig.1 equal to 1.85, 1.91, 1.93, respectively. As it can be seen, for each frequency, the phase is decreasing as the distance from the transducer increases and for increasing frequency such variation is even higher, thus demonstrating that the phase velocity increases, coherently with the graphical representation in Fig.2.

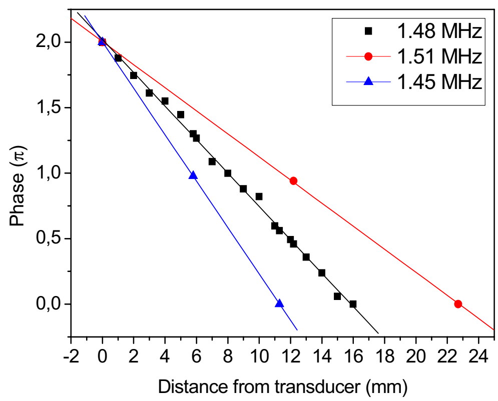


Fig.2 Phase of the backward mode S_1 vs distance

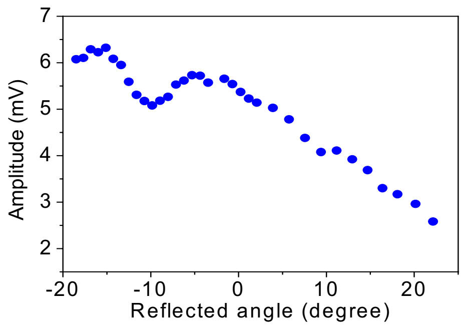
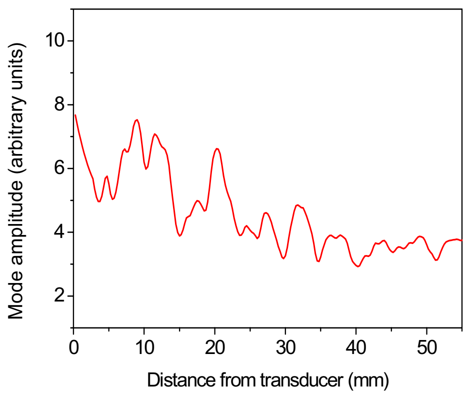


Fig.3 Amplitude of the backward propagating mode S_1 vs angle of detection from the normal at the impinging point.

Finally, the imaging effect produced by a plane boundary is set in evidence, due to the negative reflection angle. This is similar to the virtual image reconstruction that the water surface produces of an object submerged in the water: the negative reflection angle, indeed, produces a real image of an object in the same medium of the object. To this purpose, a circular transducer was coupled to the surface of a steel plate and generates Lamb modes outgoing radially from the center of the transducer, set at a distance d from the boundary line, which acts as a point object; by proper selection of the frequency f, an S_1 forward propagating mode is predominantly generated and impinges onto the limiting boundary of a steel plate b=2.05mm thick. It is reflected back both as a forward and a backward propagating mode, the former being reflected as if were coming outward from a virtual image of a plane mirror, the latter going into forming a real image in the half space of incidence at a distance d' from the limiting boundary, such that $d'/d \sim V_b/V_f$, where V_b and V_f are the velocity of the backward and forward propagating mode, respectively. The scanning of the surface where propagation is taking place was performed through an acousto-optical vibrometer, tuned at the ultrasonic frequency of the pulse in a rectangular region extended from the transducer to the limiting boundary, at different frequencies of the impinging wave, where backward modes may originate, from f_{min}=1.42MHz to f_{max}=1.47MHz. Figure 4 reports the vibration amplitude detected along the line from the emitting transducer normal to the boundary edge of the plate, averaged on the transversal direction over few millimeters, in order to avoid interference fluctuations of the modes, and relative to two frequencies f_1=1.42MHz and f_2=1.45MHz. On the adimensional graph of Fig.1, these correspond to values of the parameter $\omega b/\pi V_S$ equal to1.88 and 1.92, respectively. It can be easily seen that possible modes at these two values are more separated on the horizontal axis of the wavenumber, for the higher value (1.92) than for the lower one (1.88), the ratios of the wavenumbers being equal to the ratios of the distances d'/d where object and image are positioned. There clearly appears the difference in the higher frequency case, where maxima appear at the position of the emitting transducer, rather than in the lower frequency case, where the partial overlapping of the image with the object makes interference between modes a predominant effect.

The backward propagating mode S_1 has been then used in order to test the transmission of the forbidden region on a plate properly designed. The use of the backward mode, indeed, makes the experiment much clear and reliable, in as much as all the spurious forward propagating modes generated at discontinuities in the plate are moving back from the direction where energy of the backward mode is propagating. Generation and detection, indeed, of the mode has been done through the wedge technique and the time delay of the mode that crossed the tunneling region has been done by detecting the half maximum amplitude of the pulse train. Results are reported in Table 1 for different values of the tunneling region width at the very same value of the propagating frequency.



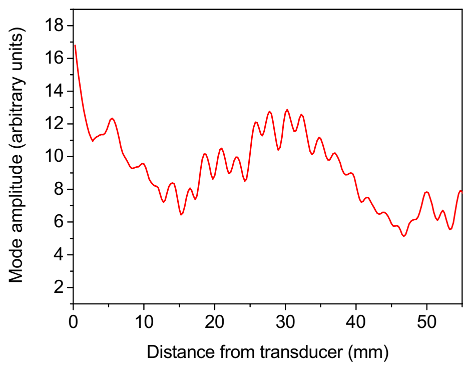


Fig.4 Amplitude of the acoustic vibration along the line from the transducer to the limiting edge of the plate at two different frequencies: f_1=1.42MHz (above) and f_2=1.45MHz (bottom).

3. Conclusions

A general presentation has been offered of the use of backward propagating mode in a plate properly designed, so as to allow a forbidden region of propagation for a below-threshold mode. Results have been given for time delay detected at different values of the region width, together with the hypothetical tunneling velocity V of the wave pulse within the forbidden region. The use of the backward propagating mode has been validated with a various phenomenology that the mode undergoes: specifically, the backward time delay of the phase, the negative refraction at the limiting boundary of a homogeneous plate and the focusing effect on the very same medium of incidence, due to the negative refraction, have been set in evidence.

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